Final Technical Report (FTR) Template

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Executive Summary:
The **Characterizing Emerging Technologies** project focuses on developing, improving and validating characterization methods for PV modules, inverters and embedded power electronics. Characterization methods and associated analysis techniques are at the heart of technology assessments and accurate component and system modeling. Outputs of the project include measurement and analysis procedures that industry can use to accurately model performance of PV system components, in order to better distinguish and understand the performance differences between competing products (module and inverters) and new component designs and technologies (e.g., new PV cell designs, inverter topologies, etc.).

1. Disseminate procedures for calibrating the Sandia PV Array Performance Model (SAPM) and validate with industry partners.
2. Provide industry with tools for precise calibration of single-diode performance models and recommend model improvements to overcome systematic model deficiencies.
3. Develop inverter test protocols to address MPPT efficiency, effects of non-unity power factor operations, and methods for determining weighted efficiencies for systems with high DC to AC ratios.
4. Develop, validate and communicate methods to characterize performance for AC modules and to verify functionality of embedded power electronics.
5. Develop, assess, validate, and communicate methods to calibrate performance models from fixed-tilt module IV data.

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Task 1: Documentation and Transfer of Sandia Array Performance Model (SAPM) Coefficient Generation Capabilities to Industry

Background: The Sandia Array Performance Model (SAPM) [1] is a semi-empirical model for predicting PV system power output and several other key performance parameters. Developed between 1991 and 2003 with industry, National Lab and DOE input, it is a component of the System Advisor Model (SAM) distributed by NREL and forms the basis for a number of performance models – both commercial and private - (e.g., PVDesignPro, SunPower, Semprius, Solimetric, etc.). The SAPM has recently been embedded into PVsyst, the most popular commercial software for modeling PV systems in the U.S. However, the capability to generate coefficients for SAPM from performance measurements of modules has not been widely available outside of Sandia. As new modules and technologies come on to the market, industry is unable to take advantage of this model due to the lack of appropriate inputs, requiring many analysts and modelers to use other performance models that are less accurate.

Prior efforts to transfer this capability to third-party labs have resulted in only limited dissemination of Sandia's measurement and analysis methods. In 2006, Fanney et al. [2] compared measured performance parameters for three modules tested outdoors at the National Institute of Standards and Technology (NIST) and Sandia. This paper described the equipment used to collect the experimental data, the test procedures and resulting performance parameters for each of the three modules. Measurements between the two laboratories were in agreement, with the power at standard rating conditions being within 1 percent for all three modules. In this study, the largest difference in measured results between the two laboratories was noted in the response of the panels to incident angles that exceeded 75 degrees. However, this paper did not directly address the question of independent SAPM coefficient generation and did not present a stepwise procedure for performing the analysis.

In 2011, Granata, et al. [3] reported on a more extensive effort to transfer this capability to TÜV Rheinland PTL, a commercial test lab in Tempe, AZ. This study included two round-robin tests on two sets of three modules each. Measurement accuracy was compared between Sandia and TÜV-PTL during the first round of testing. Error in measured short circuit current (Isc) and open circuit voltage (Voc) was less that 1.5%. However, error in voltage and current at the maximum power point (Vmp and Imp, respectively) was not as good, with a maximum error of 7.9%. These results highlighted the need to modify TÜV-PTL's measurement procedures to improve accuracy. With measurement improvements in place, during the second round of testing error between the two labs dropped to 2.3% or less, within the expected measurement equipment uncertainty. The results from this round of testing were used to independently develop SAPM coefficients at each lab. A comparison of annual energy yield predictions demonstrated prediction accuracy of less than 2%. While the transfer was deemed a success, the paper did not address the methodology in a way that was useful to other test labs; rather it served as objective proof that Sandia had "high confidence" in TUV-PTL's ability to independently test modules and develop SAPM coefficients according to our methods.

Contemporaneously with this study, Sandia published summaries describing how SAPM coefficients can be determined from measurements ([4], [5]), these summary descriptions lacked the necessary step-by-step procedures necessary for independent laboratories to carry out the process. In FY13 in response to requests from commercial laboratories and module manufacturers, we initiated an effort to further document the methods and to transfer them to industry. We established a contract with CFV Solar, a local PV test laboratory in Albuquerque, to assist in the documentation and the validation of the procedures. We chose a local laboratory because many of the characterization test procedures are not well documented and thus we anticipated that transfer would require frequent communication and technical exchanges. In addition, validation of the transfer of the methods is much more efficient when test items (modules, reference cells, etc.) can be easily exchanged between laboratories.

Task Objectives: The capability to generate coefficients for SAPM from performance measurements of modules is not widely available outside of Sandia. The objectives of this task are to produce a validated set of procedures for determining coefficients for the Sandia PV Array Performance Model (SAPM), make these publicly available and facilitate their use.

Task Results and Discussion:

From FY13-15, Sandia worked closely with CFV Solar Test Laboratory in Albuquerque, NM, to validate and document measurement and analysis procedures for determining SAPM model coefficients. These coefficients fall into three categories for which separate tests are required: temperature coefficients, AOI response, and electrical performance. The work plan was developed to address each of these test procedures as separate but interrelated. As with the TUV-PTL transfer, the work plan was designed to first validate CFV's measurement capability followed by their ability to independently generate SAPM coefficients. Two different groups of c-Si modules were used for the initial phase of this work. The validation phase was conducted using a diverse set of twelve modules, including mono-Si, poly-Si, CIGS and CdTe test samples. A significant difference from the earlier studies was that CFV was tasked with delivering a set of work instructions for conducting each test.

In FY13, we completed several milestones in the project: (1) comparison of measurement accuracy and equipment suitability between Sandia and CFV; (2) round robin module testing to ensure repeatability; and (3) initial work towards the laboratory protocol for determining module temperature coefficients from outdoor testing. The comparison and round robin testing showed that equipment commonly employed by commercial laboratories can support measurement of thermal, electrical and angle-of-incidence (AOI) properties of PV modules with accuracy similar to that obtained by Sandia when the commercial equipment is operated within certain guidelines. In FY14, we completed validation of the procedures for determining module temperature coefficients and for measuring AOI properties of PV modules. In FY15 we completed the procedure for measuring module electrical properties. All three procedures were drafted and delivered to Sandia for review and publication.

With the completion of the procedures, validation was conducted with a diverse set of twelve modules, including mono-Si, poly-Si, CIGS and CdTe test samples. The modules (and funding for CFV) were provided by a US-based module manufacturer, and thus represented not only a significant test of CFV's technical capabilities but also an important demonstration of the commercial viability of this capability. CFV independently measured module performance both indoors and outdoors, and from these measurements, coefficients for SAPM equations were obtained. The resulting coefficients were used to predict the test data to judge that the results met the desired accuracy. Sandia independently validated the module coefficients from the measured data at the conclusion of the testing.

The work with CFV to document and validate these procedures exposed two additional research needs. First, comparison of temperature coefficients determined independently by CFV (indoors, isothermal conditions) and Sandia's PSEL (outdoors, under varying temperature conditions) resulted in identifying a bias in measured temperature coefficients arising from inaccurate measurement of average cell temperature. The details were reported at 40th IEEE PVSC [6]. The bias results from inaccurate measurement of average cell temperature and may explain the variation in temperature coefficients determined by different laboratories that has been reported by others ([7], [8]). Temperature coefficients were in closer agreement after the outdoor measurement process was adjusted.

Second, outdoor characterization of module AOI response often shows an increase in the fraction of captured light at moderate values of AOI relative to the fraction captured at normal incidence. We believe that inaccuracies in the measurement process cause this result. Although comparable AOI responses were measured at both Sandia and CFV using then-current procedures, the collaboration identified opportunities to improve the procedures as well as an opportunity to develop a new method to measure AOI response indoors in a more controlled environment.

Improved measurement of AOI response outdoors was documented in [9] presented at the 42st IEEE-PVSC. Although an early version of the $f_2(\theta)$ function used in the SAPM was first published in 1997 [10], the 2015 PVSC paper [9] publicly documented its derivation for the first time. The 2015 PVSC paper also presented an improved method of accounting for diffuse radiation during AOI testing and subsequent analysis. This new method utilizes measured diffuse POA irradiance, rather than calculating this value from direct and global POA irradiance. The ability to use measured diffuse was enabled by our previous development of a flexible two-axis tracker that is capable of performing pure elevation-only off-track motion. The new method published in [9] eliminates two important sources of error in AOI measurement: error associated with the angle of incidence calibration of the reference instrumentation, and uncertainty in the calculation of the diffuse POA irradiance.

A new method to measure AOI response in a more controlled, indoor, environment is documented in [11]. This work was the result of collaboration with the University of Arizona, motivated by our work with CFV. In this study, a quantum efficiency tester was modified to facilitate angular rotation of a test cell relative to the incoming beam of collimated, monochromatic light. A standard crystalline silicon reference cell was used to compare the new indoor method to traditional outdoor AOI measurement on a two-axis solar tracker. A comparison of SAPM effective irradiance (Ee) values determined from both the empirical $f_2(\theta)$ function developed from outdoor testing and laboratory measurement of cell quantum efficiency showed good qualitative agreement between the two methods. The correspondence between the SAPM and device response terms suggests that laboratory-derived measurements may be used in place of more difficult measurements obtained outdoors using a two-axis tracker.

Task 2: Precise Calibration and Systematic Improvement of Single-diode PV Performance Models

Background: Models for photovoltaic system performance (e.g., [12], [13]) often employ a single-diode model (e.g., [14]) to compute the I-V curve for a module or string of modules at given irradiance and temperature conditions. A single-diode model requires a number of parameters to be extracted from measured I-V curves. Many available parameter estimation methods use only short circuit, open circuit and maximum power points for a single I-V curve at standard test conditions together with temperature coefficients determined separately for individual cells. In contrast, module testing frequently records I-V curves over a wide range of irradiance and temperature conditions, such as those specified in IEC 61853-1, which, when available, would improve the predictive power of parameters in the performance model.

Parameter estimation for single diode models has been challenging due to the model's use of an equation describing the relationship between current and voltage. Many available estimation methods rely on simplifying approximations, with attendant error, or optimization methods (e.g., [15]) that may be challenged to obtain reliable parameter values. Many methods (e.g., [16]) also use only a single I-V curve measured at standard test conditions (STC) whereas module testing can produce a wealth of I-V curves measured for a wide range of conditions.

Improved techniques to more precisely calibrate single diode models to measured data will significantly reduce the perceived uncertainty regarding large PV system performance predictions. Currently, no technical standard for this process exists, leading to multiple parameter sets and model files (e.g., 'PAN' files) for the same PV module technology. A recommended best practice would unify technical efforts and would reduce uncertainty in system performance predictions. Moreover, a precise method for calibrating single diode models will enable identification of systematic model deficiencies and methods for correcting the same.

In FY14, Sandia completed a new algorithm for calibrating single-diode models. NREL completed a separate algorithm using different mathematical methods and relying on different types of measurements. In addition, industry has reported several additional, independently developed techniques.

Task Objectives: In collaboration with PVPMC participants we will evaluate different technical approaches for calibrating single-diode models to recommend a best practice. We will employ the precision calibration methods to recommend improvements to popular single-diode performance models (e.g., PVsyst, CEC) to overcome systematic model deficiencies.

Task Results and Discussion: Sandia's methods for calibrating single diode models are detailed in [17]. Here, we presented a new method for estimating parameters for single diode models, illustrated by application to the single diode model specified in [2]. The method requires prior determination of module temperature coefficients for Isc and Voc and a set of I-V curves measured across a range of effective irradiance and cell temperature. The method first estimates the diode factor from measured Voc for a set of I-V curves, applies an iterative procedure to obtain values for I_L, I_O, R_{SH}, and R_S for each

I-V curve, and finally, obtains parameters for the single diode model by a series of regressions.

We applied our method to recover parameters from I-V curves that were computed from several assumed sets of parameters for a single diode model to verify the method's robustness. Being a sequential estimation algorithm, values for I_L, I_O, R_{SH}, and R_S for each fitted I-V curve are conditional on the value for the diode factor n. Small errors in the recovered diode factor can result in significant differences in the values for the other parameters. The diode factor is estimated using a linear relationship that is an approximation derived from the single diode equation. We have observed that the other parameters for an I-V curve are quite sensitive to small changes in the diode factor. Consequently our method's robustness may be improved by additional refinement of the technique for recovering the diode factor.

Our method involves numerical convergence at a number of steps. However, the initial values for the optimizations are not selected with randomness, and hence, subject to variation in machine precision and software (e.g., Matlab versions) we believe our method to be reliable.

Having outlined the method in detail we believe it to be accessible to one with an adequate mathematical and engineering background. However, we believe that the method, as described in this report, offers further opportunities for simplification. For example, the initial estimate of R_{SH} requires a fairly involved set of calculations (i.e., coordinate transformations, spline fitting and numerical integration) yet the initial estimate of R_{SH} is later replaced with an updated value. Consequently, a less accurate initial estimate obtained by a simpler process may be just as good. We tested some simpler methods and found that most of the resulting values fell within expected ranges for all parameters. However the alternative methods also increased somewhat the number of I-V curves for which the parameter estimation failed and so we have retained the more complicated technique. We view the complexity involved in the initial estimate of R_{SH} as indicating an opportunity to improve our algorithm.

The method describe in [17] was developed using the De Soto single diode model [13]. The model coded into the PVsyst software package (described in [18]) differs substantially from that in [13]. We extended our techniques to obtain parameters for the PVsyst model and published the results in [19].

Algorithms to estimate parameters for the De Soto model [13] and PVsyst have been coded into MatLab and will be distributed to the public in a planned upcoming release of PV_LIB. Additionally, a patent application, 62/134,413, "Methods for estimating photovoltaic module performance model parameters" has been submitted.

Sandia's developed expertise with single diode models resulted in invitations to collaborate with other research efforts on this topic, resulting in co-authorship of an analysis exploring likelihood methods (i.e., a Bayesian approach) to fitting IV curves [20] and a technique to adjust PVsyst parameters to minimize differences between predicted and observed efficiency [18].

At the conclusion of FY15 the comparison among parameter estimation methods was incomplete. Benchmark test cases had been distributed to interested participants but responses had not been evaluated. Analysis to propose and validate improvements to popular single diode models had not begun. These efforts were terminated at the conclusion of FY15.

Task 3: Develop and Validate New Inverter Test Protocols

Background: In 2004 Sandia National Laboratories, together with BEW Engineering, published a protocol described laboratory methods for measuring and reporting inverter efficiency in a draft document entitled “Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems”. This protocol, commonly referred to as the “Sandia Inverter Test Protocol,” was formally adopted by the California Energy Commission as a requirement for all inverters participating in its incentive programs. As a result, this protocol has been effectively adopted for all inverters sold in the US.

However, the PV industry has changed significantly since this protocol was originally published. PV modules have become much less expensive, inverters are implementing new algorithms (e.g., optimized maximum power point tracking), and grid integration challenges are increasing as more PV systems are being connected to the grid (e.g., maintaining stable feeder voltage). Due the drop in module cost, system integrators are building systems with DC/AC ratios significantly above one. Inverters are implementing new algorithms to combat conditions such as intermittent irradiance conditions (from passing clouds) that can challenge the inverter’s ability to remain at the maximum power point. In addition, PV systems are now being required to operate at non-unity power factors to help utilities maintain stable voltage on their distribution systems; sinking or sourcing of VARs can increase internal losses in the inverter and reduce power conversion efficiency.

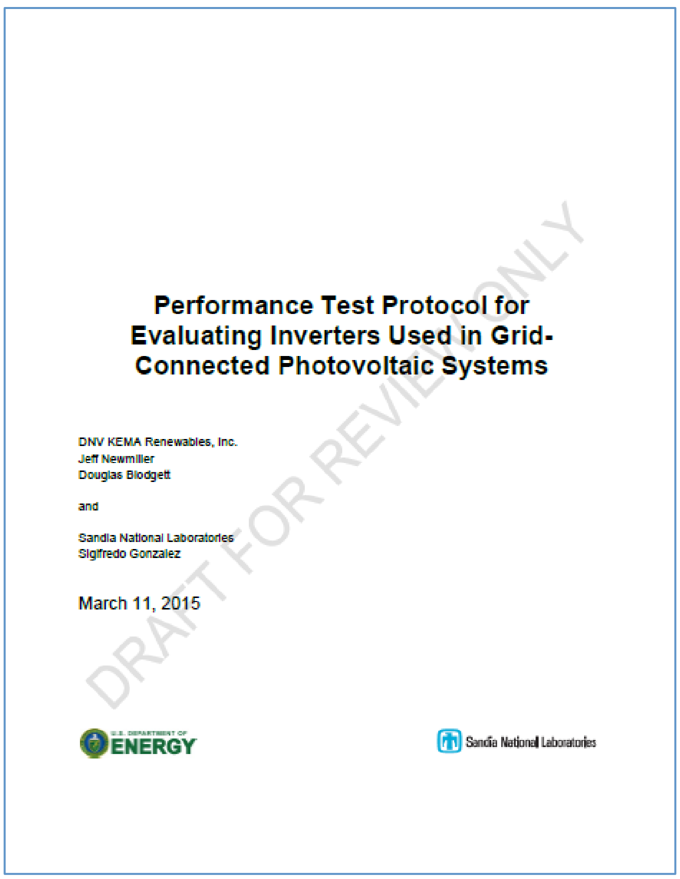
All of these operations affect inverter efficiency in ways that are not quantified for inverters being offered in the marketplace. The Sandia Inverter Test Protocol does not include evaluation of the effects of maximum power point tracking (MPPT), of high DC/AC ratios or of operation at non-unity power factor on inverter efficiency. Therefore a new inverter performance protocol will be developed to assess and quantify two key inverter performance characteristics for new inverter capabilities.

A European standard (EN50530) that describes one method for determining this efficiency was published in 2010 and later revised in 2013. The methods described in the standard rely on the ability to simulate a PV array under dynamic irradiance conditions using a programmable power supply (PV simulator) with a high degree of accuracy. The MPPT efficiency is then determined by connecting the inverter to the simulator and running it through a predetermined set of irradiance ramps and measuring the AC output of the inverter. This measured output is divided by the theoretical output of the simulator to determine the MPPT efficiency. A major limitation of this methodology is that it assumes that the simulator produces its theoretical output with a high degree of accuracy.

Task Objectives: To develop new inverter test protocols to include; 1) the effects of operation at non unity power factor on conversion efficiency 2) the effects of high DC to AC ratio (> 1) on how the weighted efficiency of the inverter is calculated and 3) maximum power point tracking (MPPT) efficiency. The new test protocols will be published as an industry “Recommended Practice” for characterizing these aspects of inverter performance and submitted to UL for conversion to an ANSI standard.

Task Results and Discussion: This task was planned for completion at the end of FY14. An evaluation of the maximum power point tracking (MPPT) efficiency proved unsuccessful in FY14, however enough was learned to complete this portion of the inverter test protocol in FY15.

The results of this task are detailed in [21] and [22]. The report [21] has been submitted to UL for approval to become an ANSI Standard. Once converted to a standard, it will provide performance test specifications and requirements for inverters to be used in grid-tied photovoltaic systems. The report specifies the type test that shall be performed to measure and report the maximum continuous power rating, conversion efficiency, and tare losses of inverters used in grid-connected photovoltaic systems. Interconnection equipment that connects distributed resources to an electrical power system are expected to do so efficiently. Standardized test procedures are necessary to establish methods for verifying inverter performance that leads to comparable results. These test procedures are provided as a repeatable, independent means of measuring inverter performance regarding maximum continuous power rating, conversion efficiency, and tare loss characteristics.



Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems

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March 11, 2015

DRAFT FOR REVIEW ONLY

U.S. DEPARTMENT OF ENERGY

Sandia National Laboratories

Figure 3.1. Procedure submitted to UL.

Task 4: Methods for Characterizing AC Modules

Background: The use of microinverters removes the necessity to attempt to match the DC current through each PV module in a string of modules, thus allowing greater flexibility regarding module placement and orientation. Systems with microinverters typically operate at 240 or 480 AC volts, while systems with central inverters operate at up to 600 or 1000 DC volts; this reduction in voltage reduces the risk of arc faults, which are the leading source of fires caused by PV systems. However, these potential advantages come with the disadvantages of increased system component counts and potential failure points.

Typically, microinverters are discrete components in a PV system. Thus, the PV modules and the inverters may be characterized separately and system output can be modeled using combinations of existing models, e.g., [1] or [13] with either [23] or [24]-4]. Some manufacturers are integrating a microinverter into a PV module, combining the separate elements into a single unit, termed an "AC module. In an AC module, there is no ready access to the DC portion of the circuit. [25].

Without access to the DC portion of the circuit, and without the ability to separate the PV module from the inversion electronics, it is not possible to characterize the PV module and the microinverter separately, which prevents application of existing performance models to AC modules.

Task Objectives: Test protocols will be available for integrated AC modules addressing module characterization and performance modeling as well as functionality testing of the integrated power electronics. Such protocols will allow accurate characterization of performance and predictions of the power and energy which may be produced under a given set of climatic conditions, thus reducing risk and costs associated with adopting systems of AC modules.

Task Results and Discussion:

AC module performance work conducted by Sandia in FY13 focused on 1) developing the measurement hardware, 2) performing measurements on a prototype set of AC modules and 3) developing initial performance descriptions. The work culminated in a paper [26] published and presented at the 39th Photovoltaic Specialists Conference (PVSC). FY2014 work completed the characterization of several additional modules, identification of performance parameters of interest, and development of a predictive model.

In parallel, microinverter interoperability efforts at Sandia in FY13 consisted of building the microinverter interoperability test bed, including infrastructure, measurement equipment, and obtaining test specimens [27]. Performing IEEE interconnection standard tests and preliminary data analysis resulted in another paper at the 39th PVSC [28]. FY14 work further investigated violations found in microinverter interoperability standards from voltage magnitude, as well as more thorough investigations on harmonic distortion and possibly anti-islanding.

The details of the test procedures, electrical equipment requirements, parameter determination methods and validation of a new AC module are presented in [29]. The model seeks to predict the active AC power which is produced by an AC module at a given temperature, under a given irradiance and absolute air mass condition. The coefficients which describe the AC module performance are somewhat similar to the coefficients found in performance models for standalone PV modules, however, several reference conditions must be specified since all AC modules may not be in the typical operating state (i.e. may be self-limiting) at the conventional reference conditions of 1000 W/m2, ASTM G173 spectrum, and 25 °C cell temperature. The performance model includes descriptions of the performance when the AC module is self-limiting or “clipping” its power, as well as describing performance when the AC module is under extremely low-irradiance such as at night. The addition of limiting conditions for low-irradiance and self-limiting will improve the energy yield predictions over long periods of time.

The model for the typical operating state is formed as a series of multipliers to a reference power. The multipliers are a set of normalized sub-models that describe the normalized performance changes of the AC module as a function of a particular variable (or variables). Thus the model is flexible, since new sub-models may be introduced which better describe the performance of the AC module as a function of the particular variable. We have proposed a series of recommended sub-models for use within the model.

We have also described a series of outdoor tests that may be performed in order to generate the necessary performance coefficients for use in the model. These tests attempt to hold constant some environmental conditions surrounding the AC module while allowing specific conditions to vary.

Once the series of tests have been conducted, we have shown how to transform the test data into the model coefficients. Where we have suggested specific sub-models (e.g. incident angle modifier models, cell temperature models, air mass models) we have shown the process to obtain model coefficients for those sub-models from test data.

Lastly, we have shown that for the AC modules that we tested, the model is capable of predicting the power of an AC module in a fixed-tilt orientation with a root mean square error of 1 %. The model predicted the energy of an AC module system over the course of 9 days to within 1.4 % of the actual produced energy.

The AC module performance model presented here may be used to characterize and subsequently predict the AC energy output of system of AC modules. The model may also be used to compare the performance of two different AC modules. We further propose that the model may be useful in establishing a performance standard for AC modules, as no such standard currently exists.

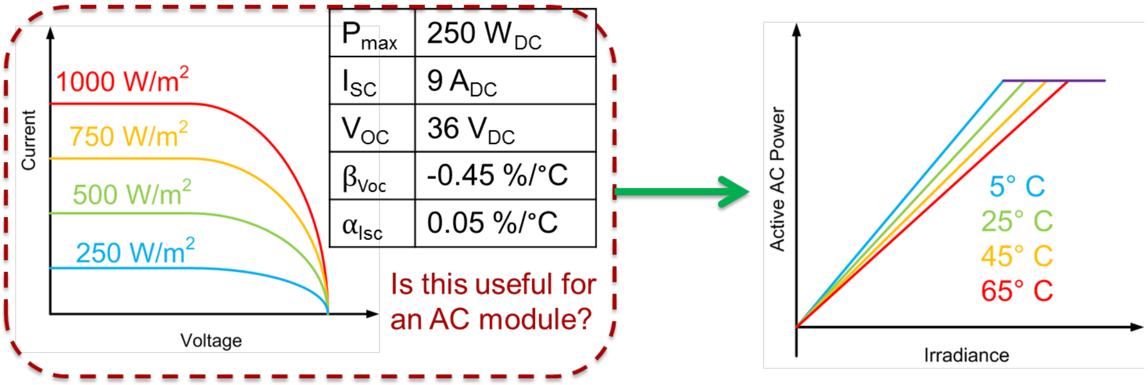

Figure 4.1. Proposed AC module rating method for manufacturer’s data sheets

Task 5: Accurate Calibration of Performance Models Using Only Monitored System Data

Background: Performance models for photovoltaic modules are traditionally calibrated from measurements of module output under carefully controlled conditions. Most commonly, module performance is characterized by obtaining I-V curves indoors at a couple of fixed conditions (e.g., STC and low irradiance) and by using temperature coefficients taken from manufacturer's datasheets. More sophisticated methods (e.g., Sandia's method) use a series of tests on a 2-axis tracker, which measure I-V curves and module temperatures outdoors under a range of conditions, or using a solar simulator operated at a wide range of conditions. Both methods have their advantages and disadvantages, but in either case, expensive hardware is required to perform the calibration. In contrast, monitoring electrical performance for systems outdoors on fixed racking is substantially cheaper and widely practiced at outdoor test facilities. There is a lack of a validated, well-documented method to obtain accurate performance models using only data from passively-monitored systems.

A method for calibrating currently available models will produce coefficients for SAPM or one of the single-diode models (e.g. De Soto, PVsyst). SAPM comprises empirical expressions for short circuit current, open circuit voltage, and the maximum power point. The De Soto model [13] uses a single diode equivalent circuit to represent a module's IV curve. The software package PVsyst also represents a PV module as a single diode equivalent circuit albeit with some different equations than the De Soto model. Calibration of each model determines a set of module specific coefficients, including estimates for reflection losses at the module surface when the module is not normal to the sun and the variation in current due to the spectral content of incident irradiance.

Task Objectives: Investigate the feasibility of calibrating performance models by using IV curves measured outdoors from a fixed tilt array, and the accuracy of the resulting models.

Task Results and Discussion: Data used for this task came from two different sources. First, Sandia, NEDO, and Tokyo Institute of Technology are working together with a unique dataset from Los Alamos, NM, where NEDO has installed a variety of PV modules and has measured both module level IV curves as well as PV system output data. Fixed tilt data was collected from five PV modules representing a range of technologies. Electrical, irradiance, and temperature data was collected by NEDO every 5 minutes outdoors at Los Alamos, NM, between July 25th, 2012 and August 30th, 2013. For each module, I-V curves, plane-of-array (POA), direct normal irradiance (DNI), and cell temperature (T_c) were measured. Short-circuit current (I_{sc}), open current voltage (V_{oc}), and the max power point (I_{mp}, V_{mp}, and P_{mp}) are extracted from each I-V curve. Module datasheets provide temperature coefficients and system specifications. Together we are collaborating in the analysis of this data to compare the performance of different calibrated PV performance models.

Second, we collaborated with NREL on the performance characterization of the modules deployed in the multi-year mPERT project [30]. In this project, a new publicly available data set was developed specifically for use in validating performance models.

Modules representing all technologies available in 2010 when the project began were deployed at fixed tilt for one-year periods at three climatically diverse locations (Cocoa, Florida; Eugene, Oregon; and Golden, Colorado). IV sweeps were collected for each module simultaneously with local weather and irradiance. At the conclusion of the fixed tilt deployment, a total of 24 modules were sent to Sandia for detailed performance characterization on our two-axis trackers.

In [31], presented at EU-PVSEC in 2014, we demonstrated that monitored system data could be used to calibrate models for predicting output from PV modules. Both the SAPM and CEC models were calibrated using system data for for a variety of cell technologies, including mono and polycrystalline silicon, copper Indium selenide and tandem junction amorphous silicon. Prediction error for of PMP using the SAPM model was within 10% of measured power over a wide range of environmental conditions spanning low and high irradiance and module operating temperature. Prediction error of PMP using the CEC model was also within 10% of measured power with the exception of the module based on amorphous silicon cell technology. Here, prediction accuracy was closer to 15%. This result is not surprising though given that the tandem amorphous cell is effectively a two-diode device, whereas the CEC model represents the cell as a single diode equivalent circuit. These prediction errors are roughly twice as great as the ~5% prediction errors observed for models calibrated for data obtained outdoors using a two-axis tracker, or indoors using a solar simulator [4, 5].

The calibration methods presented in [31] used temperature coefficients from module data sheets rather than measured values. In the paper, we speculated that model prediction errors could be reduced substantially to be comparable to those from models calibrated using two-axis tracker or solar simulator data, if measured temperature coefficients were used rather than assuming datasheet values. In [32], presented at the 6th WCPEC, we demonstrated an improved method of accounting for temperature coefficients still using only monitored system data. We first fit the model using a datasheet value and observed a bias in predicted V_{MP} that is systematic in module temperature, indicating an incorrect value for the temperature coefficient. To adjust the temperature coefficient from the datasheet value, a regression line was fit to a scatterplot of measured vs modeled V_{mp} and its slope was used to scale the datasheet temperature coefficient. The adjusted temperature coefficient was then used to recalibrate the models and the process was repeated until predicted V_{MP} showed no bias. We found that generally the temperature coefficients stabilize after 2 or 3 iterations and removed the systematic biases we found primarily in the V_{OC} and V_{MP} predictions.

Development of the fitting method uncovered two issues worth further investigation. We observed that the terms involved in modeling Isc required substantial data to estimate, and that estimates of these terms varied for the same module monitored at different locations. We also observed that other model terms could be determined with a surprisingly small amount of data.

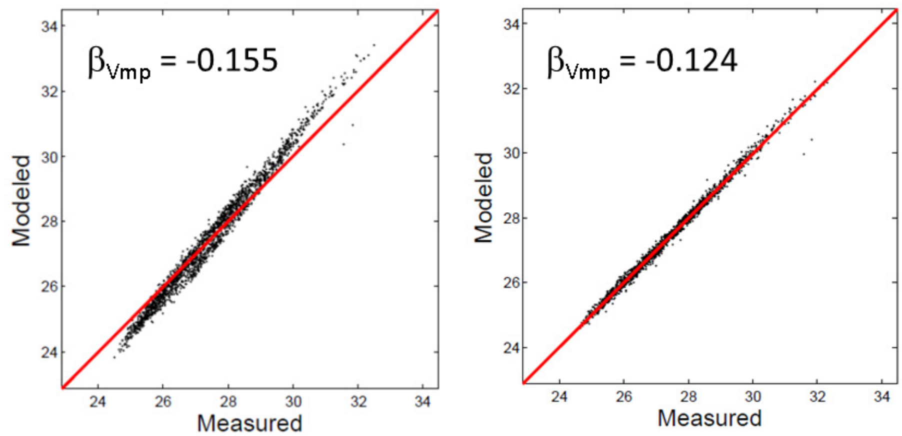

Figure 5.1: Prediction in VMP before (left) and after(right) the temperature coefficient adjustment.

In [33], presented at the 42nd IEEE-PVSC, we used the mPERT data for a detailed investigation on the impact of spectral variability on short circuit current. In this paper, we demonstrated methods to isolate the air mass modifier and short circuit current at STC using data collected at fixed tilt orientation. Further, we investigated the dependence of location and time of year on these parameters. We found that I_{SC0} was systematically higher at Cocoa than at the other two locations. Estimated I_{SC0} values changed very little throughout the year. The air mass modifiers, on the other hand, were highly variable throughout the year at each of the three locations. In general, we found that the air mass modifiers were higher in the winter than in the summer. These effects might be related to the higher absolute humidity in the summer, and overall higher absolute humidity at Cocoa.

This confirmed our prior observations and an emerging belief within the PV performance and modeling community; the use of a single polynomial model in AMa to model the effect on module current of spectral variation introduces uncertainty into module performance predictions. The single polynomial does not represent systematic locational, seasonal or time of day variation in measured module output. As a result, we view the current polynomial model form as not suitable. These results indicate opportunities to improve prediction accuracy by improvements to the air mass modifier component of performance models.

Finally, in [34], also presented at the 42nd IEEE-PVSC, we investigated the dependence of a model's prediction accuracy on the amount of data used to calibrate the model's parameters. We found that all model parameters other than the air mass modifier could be reliably estimated from a relatively few (roughly 100) I-V curves measured outdoors with the module on fixed tilt racking. Comparison of sampling techniques between simple random and stratified random (see Figure 5.2) suggests that prediction accuracy is not sensitive to I-V curve selection as long as the range of environmental operating conditions is represented in the data. Stratified sampling ensures this by breaking the data into smaller bins prior to sampling.

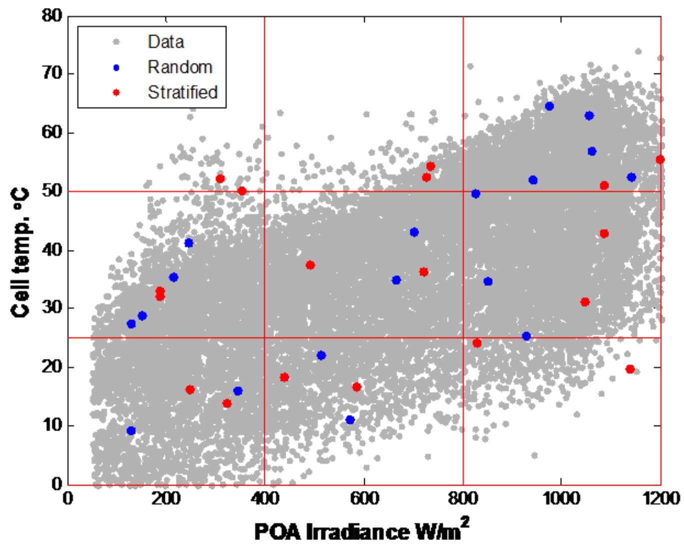

Figure 5.2: Simple and stratified random sampling. In simple random sampling, data points are selected at random from the entire population. In stratified random sampling, data points are selected at random from within each bin indicated by the red grid.

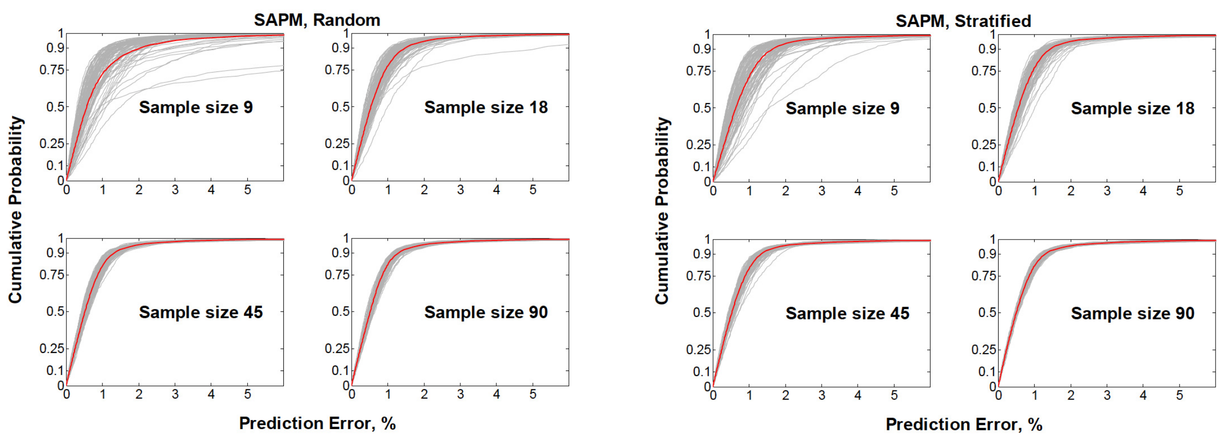

Figure 5.3: Distributions of absolute Pmp error fir the SAPM model for a moncrystalline silicon module. Both sampling methods result in model convergence at ~ 90 samples, although stratified sampling ensures that a wide enough range of environmental conditions are used to be representative of normal operating conditions.

However, estimating a reliable air mass modifier proved to have multiple challenges [33]. The first challenge is to obtain a sufficient number of IV curves during clear-sky conditions over a wide range of air mass values. Secondly, even with sufficient data, the usual form of the air mass modifier function, i.e., a 4th order polynomial in air mass, does not laccurately represent the diurnal and seasonal variation in module current due to changing solar spectrum. The prediction error due to the mis-specified air mass modifier tends to dominate prediction error from the remainder of the module performance model. It may be that an alternate form for the air mass function will prove to be both suitable in terms of prediction accuracy as well as stable when estimated from small samples.

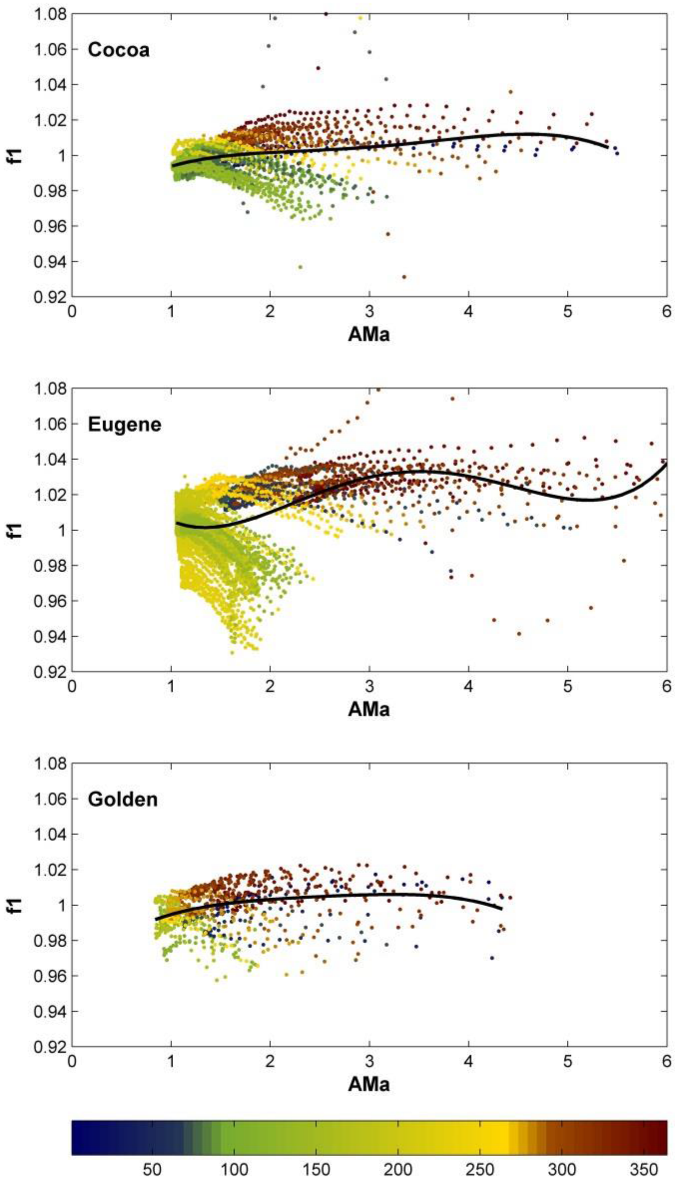

Fig. 5.4. Air mass modifier for a c-Si module, data (colored by day of year) along with the f1 (AMa) polynomial. Variation in the f1 response throughout the year and at different locations is due to variation in solar spectrum. The polynomial function typically used to represent air mass does not capture these variabilities.

Accomplishments:

Peer-Reviewed Journal Articles:

C. W. Hansen and K. A. Klise, Monitored System Data Requirements for Photovoltaic System Model Calibration, Journal of Photovoltaics (in preparation)

Conference Publications:

M. G. Farr and J. S. Stein, "Spatial Variations in Temperature across a Photovoltaic Array," 40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014

S. Gonzalez, J. Neely, M. Ropp, “Effect of Non-unity Power Factor Operation in Photovoltaic Inverters Employing Grid Support Functions”; 40th IEEE Photovoltaics Specialists Conference, Denver, CO, 2014

S. Gonzalez, J. Stein, A. Fresquez, M. Ropp and D. Schutz, “Performance of Utility Interconnected Photovoltaic Inverters Operating Beyond Typical Modes of Operation,” 39th IEEE Photovoltaic Specialists Conference, Tampa, FL, 2013

C. W. Hansen, A. Luketa-Hanlin and J. S. Stein, “Sensitivity of Single Diode Models for Photovoltaic Modules to Method Used for Parameter Estimation,” 28th EU PVSEC, Paris, France. 2013

C. Hansen, “Estimation of Parameters for Single Diode Models from Measured I-V Curves,” 39th IEEE Photovoltaic Specialists Conference, Tampa, FL, 2013

C. W. Hansen, K. A. Klise and J. S. Stein, “Data Requirements for Calibration of Photovoltaic System Models Using Monitored System Data,” 42nd IEEE Photovoltaic Specialists Conference. New Orleans, LA, 2015

C. Hansen, M. Farr, L. Pratt, “Correcting Bias in Measured Module Temperature Coefficients,”40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014

C. W. Hansen, K. A. Klise, J. S. Stein, Y. Ueda, K. Hakuta, “Photovoltaic System Model Calibration Using Monitored System Data,” World Conference on Photovoltaic Energy Conversion, November 2014.

C. W. Hansen, M. Farr, L. Pratt, “Correcting Bias in Measured Module Temperature Coefficients,” 40th IEEE Photovoltaics Specialists Conference, Denver, CO, 2014

B. King, D. Riley, C. Robinson and L. Pratt, “Recent Advancements in Outdoor Measurement Techniques for Angle of Incidence Effects,” 42nd IEEE Photovoltaic Specialist Conference. New Orleans, LA, 2015

K. A. Klise, C. W. Hansen and J. S. Stein, “Dependence on Geographic Location of Air Mass Modifiers of Photovoltaic Module Performance Models,” 42nd IEEE Photovoltaic Specialist Conference. New Orleans, LA, 2015

K. Klise, C. Hansen, J.S. Stein, Y. Ueda, and K. Hakuta, “Calibration of Photovoltaic Module Performance Models Using Monitored System Data, 29th EU Photovoltaic Solar Energy Conference, Amsterdam, Netherlands, 2014

B. Marion, A. Anderberg, C. Deline, J. del Cueto, M. Muller, G. Perrin, J. Rodriguez, S.

Rummel, T. J. Silverman, F. Vignola, R. Kessler, J. Peterson, S. Barkaszi, N. Riedel, L. Pratt, B. King, “New Data Set for Validating PV Performance Models,” 40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014

J. Newmiller, W. Erdman, J. S. Stein, and S. Gonzalez, “Sandia Inverter Performance Test Protocol Efficiency Weighting Alternatives,” Sandia National Laboratories, Albuquerque, NM, 40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014

B. G. Potter, Jr., C. W. Hansen, J. H. Simmons and B. H. King, Incidence-angle dependent external quantum efficiency: laboratory characterization and use in irradiance-to-power modeling,” 42nd IEEE Photovoltaic Specialists Conference. New Orleans, LA, 2015

J.E. Quiroz, S. Gonzalez and J. S. Stein, “PV Microinverter Test bed for Interoperability,” 39th IEEE Photovoltaic Specialists Conference, Tampa, FL, 2013

D. Riley, “Performance Model for Characterizing AC Modules and Predicting Their Power,” 42nd IEEE Photovoltaic Specialists Conference. New Orleans, LA, 2015

D. Riley, J. Stein and J. Kratochvil, “Testing and Characterization of PV Modules with Integrated Microinverters,” 39th IEEE Photovoltaic Specialists Conference, Tampa, FL, 2013

B. Zaharatos, M. Campanelli, C. Hansen, K. Emery, L. Tenorio, “Likelihood Methods for Single Diode Model Parameter Estimation from I-V Curve Data with Noise,” 40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014

Sandia Technical Publications:

D. M. Riley, C.W. Hansen, M. Farr, “A Performance Model for Photovoltaic Modules with Integrated Microinverters,” SAND2015-0179, Sandia National Labs, Albuquerque, NM, 2015

C. W. Hansen, “Parameter Estimation for Single Diode Models of Photovoltaic Modules,” SAND2015-2065, Sandia National Labs, Albuquerque, NM, 2015

C. W. Hansen, “Estimating Parameters for the PVsyst Version 6 Photovoltaic Module Performance Model,” SAND2015-8598, Sandia National Labs, Albuquerque, NM, 2015

J.E. Quiroz, S. Gonzalez, B. King, D. Riley, J. Johnson, J. Stein, Photovoltaic Microinverter Testbed for Multiple Device Interoperability, SAND2014-19836, Sandia National Labs, Albuquerque, NM, 2014

Patent Applications:

A U.S. Provisional Patent Application Number 62/134,413, was filed March 17, 2015, entitled “Methods for estimating photovoltaic module performance model parameters”.

Path Forward:

There are several potential opportunities identified in this research program that would be worth considering for future proposals.

The first is the creation of an open, public archive for PV module performance coefficients. Currently, module parameters come with an uncertain pedigree and in many cases several different parameter sets are available for the same module model number. This is a problem in industry because it leads to disagreement on which parameter sets are best. It might even make sense to create a public archive of performance measurements (e.g., IEC 61853-1 data) so that modelers can use the parameter derivation method of their choice.

Results on this research indicated the importance of being able to quickly and cheaply assess the spectral characteristics of full scale PV modules. While very expensive lab equipment is available to measure the spectral response on modules, it is not widely available, and the actual measurement is performed at a small spatial scale and may not be representative of a full module's response, especially for thin films. Further development of outdoor techniques to characterize the spectral response is still needed.

Further results of this project have presented strong evidence that some of the assumptions used by popular module performance models (e.g., PVsyst) are not a good representation of actual behavior. For example, PVsyst assumes that the series resistance variable in the single diode expression is a constant value when laboratory testing appears to indicate series resistance increases significantly at low irradiance. This assumption results in significant errors during low irradiance periods of simulation. Further research could better define this pattern and a new version of the PVsyst model could be developed.

Finally, procedures for testing PV modules outdoors in order to calibrate the Sandia PV Array Performance Model have not been completed as of the end of the FY and there is no remaining budget left to support this work. Sandia plans to present DOE with a proposal detailing what it would take in terms of time and budget to finish this work and get the procedures published and available for test labs to use.

References:

[1] King, D., Boyson, W., Kratochvil, J. (2004). Photovoltaic Array Performance Model, SAND2004-3535, Sandia National Laboratories, Albuquerque, NM, December 2004.

[2] Fanney, A.H., et al., Comparison of photovoltaic module performance measurements. Journal of Solar Energy Engineering, 2006. 128(2): p. 152-159.

[3] Granata, J.E., et al. Successful Transfer of Sandia National Laboratories' Outdoor Test technology to TUV Rheinland Photovoltaic Testing laboratory. in IEEE Photovoltaic Specialists Conference, 2011. Seattle, WA.

[4] Hansen, C., et al. Parameter Uncertainty in the Sandia Array Performance Model for Flat-Plate Crystalline Silicon Modules. in 37th IEEE Photovoltaics Specialists Conference, 2011. Seattle, WA.

[5] Hansen, C., D. Riley, and M. Jaramillo. Calibration of the Sandia Array Performance Model Using Indoor Measurements in IEEE Photovoltaic Specialists Conference, 2012. Austin, TX.

[6] Hansen, C.W., M. Farr, and L. Pratt. Correcting Bias in Measured Module Temperature Coefficients. in 40th IEEE Photovoltaic Specialist Conference, 2014. Denver, CO.

[7] Fatehi, J. Results of Module Testing Round Robin. in 2014 PV Performance Modeling Workshop, 2014. Santa Clara, CA: Sandia National Laboratories.

[8] Joshi, M. Toward Reliable Module Temperature Measurement: Considerations for Indoor Performance Testing. in 2014 PV Performance Modeling Workshop, 2014. Santa Clara, CA: Sandia National Laboratories.

[9] King, B.H., et al. Recent Advancements in Outdoor Measurement Techniques for Angle of Incidence Effects. in 42nd IEEE Photovoltaic Specialist Conference, 2015. New Orleans, LA.

[10] King, D.L., J.A. Kratochvil, and W.E. Boyson. Measuring solar spectral and angle-of-incidence effects on photovoltaic modules and solar irradiance sensors. in Photovoltaic Specialists Conference, 1997., Conference Record of the Twenty-Sixth IEEE, 1997.

[11] Potter, B.G., et al. Incidence-angle Dependent External Quantum Efficiency: Laboratory Characterization and Use in Irradiance-to-Power Modeling. in 42nd IEEE Photovoltaic Specialist Conference, 2015. New Orleans, LA.

[12] Mermoud, A. and T. Lejeune. Performance Assessment Of A Simulation Model For Pv Modules Of Any Available Technology. in 25th European Photovoltaic Solar Energy Conference, 2010. Valencia, Spain.

[13] De Soto, W., S.A. Klein, and W.A. Beckman, Improvement and validation of a model for photovoltaic array performance. Solar Energy, 2006. 80(1): p. 78-88.

[14] Gray, J.L., The Physics of the Solar Cell, in Handbook of Photovoltaic Science and Engineering, A. Luque, Hegedus, S., Editor. 2011, John Wiley and Sons.

[15] Dobos, A., An Improved Coefficient Calculator for the California Energy Commission 6 Parameter Photovoltaic Module Model. Journal of Solar Energy Engineering, 2012. 134(2).

[16] Duffie, J.A. and W.A. Beckman, Solar Engineering of Thermal Processes 2006: Wiley.

[17] Hansen, C., Parameter Estimation for Single Diode Models of Photovoltaic Modules, SAND2015-2065, Sandia National Laboratories, Albuquerque, NM, 2015.

[18] Sauer, K.J., T. Roessler, and C.W. Hansen, Modeling the Irradiance and Temperature Dependence of Photovoltaic Modules in PVsyst. Photovoltaics, IEEE Journal of, 2015. 5(1): p. 152-158.

[19] Hansen, C.W., Estimating Parameters for the PVsyst Version 6 Photovoltaic Module Performance Model, SAND2015-8598, Sandia National Laboratories, Albuquerque, NM, 2015.

[20] Zaharatos, B., et al. Likelihood Methods for Single-Diode Model Parameter Estimation from Noisy I-V Curve Data. in 40th IEEE Photovoltaic Specialist Conference, 2014. Denver, SO.

[21] Newmiller, J., Blodgett, D., Gonzalez, S., Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems, SAND2015-4418R, Sandia National Laboratories, Albuquerque, NM, 2015.

[22] J. Newmiller, W. Erdman, J. S. Stein, and S. Gonzalez, “Sandia Inverter Performance Test Protocol Efficiency Weighting Alternatives,” Sandia National Laboratories, Albuquerque, NM, 40th IEEE Photovoltaic Specialists Conference, Denver, CO, 2014.

[23] King, D., Gonzalez, S., et al. (2007). Performance Model for Grid-Connected Photovoltaic Inverters. SAND2007-5036, Sandia National Laboratories, Albuquerque, NM, September 2007.

[24] Driesse, A., Jain, P., et al. (2008). Beyond the Curves: Modeling the Electrical Efficiency of Photovoltaic Inverters. Proc. 33rd IEEE Photovoltaic Specialists Conference, vols. 1-4: 1935-1940.

[25] National Fire Protection Association. (2014). NFPA 70: National Electric Code 2014.

[26] D. Riley, J. Stein and J. Kratochvil, “Testing and Characterization of PV Modules with Integrated Microinverters,” 39th IEEE Photovoltaic Specialist Conference, Tampa, FL, 2013.

[27] J.E. Quiroz, S. Gonzalez, B. King, D. Riley, J. Johnson, J. Stein, Photovoltaic Microinverter Testbed for Multiple Device Interoperability, Albuquerque, NM, 2014. SAND2014-207844

[28] J.E. Quiroz, S. Gonzalez and J. S. Stein, “PV Microinverter Test bed for Interoperability,” 39th IEEE Photovoltaic Specialists Conference, Tampa, FL, 2013.

[29] Riley, D., C.W. Hansen, and M. Farr, A Performance Model for Photovoltaic Modules with Integrated Microinverters, SAND2015-0179, Sandia National Laboratories, Albuquerque, NM, 2015.

[30] Marion, W., et al., User’s Manual for Data for Validating Models for PV Module Performance, NREL/TP-5200-61610, National Renewable Energy Laboratory, 2014.

[31] Hansen, C.W., et al. Calibration of Photovoltaic Module Performance Models Using Monitored System Data. in 29th European PV Solar Energy Conference, 2014. Amsterdam, The Netherlands.

[32] Hansen, C.W., et al. Photovoltaic System Model Calibration Using Monitored System Data. in 6th World Conference on Photovoltaic Energy Conversion, 2014. Kyoto, Japan.

[33] Klise, K.A., C.W. Hansen, and J.S. Stein. Dependence on Geographic Location of Air Mass Modifiers For Photovoltaic Module Performance Models. in 42nd IEEE Photovoltaic Specialist Conference, 2015. New Orleans, LA.

[34] Hansen, C., K.A. Klise, and J.S. Stein. Data Requirements for Calibration of Photovoltaic System Models Using Monitored System Data. in 42nd IEEE Photovoltaic Specialist Conference, 2015. New Orleans, LA.